Single Rotor Turbine Engine Proof of Concept

Subcontract No. 04550-001-04 4X

Phase One Review

August 25, 2004

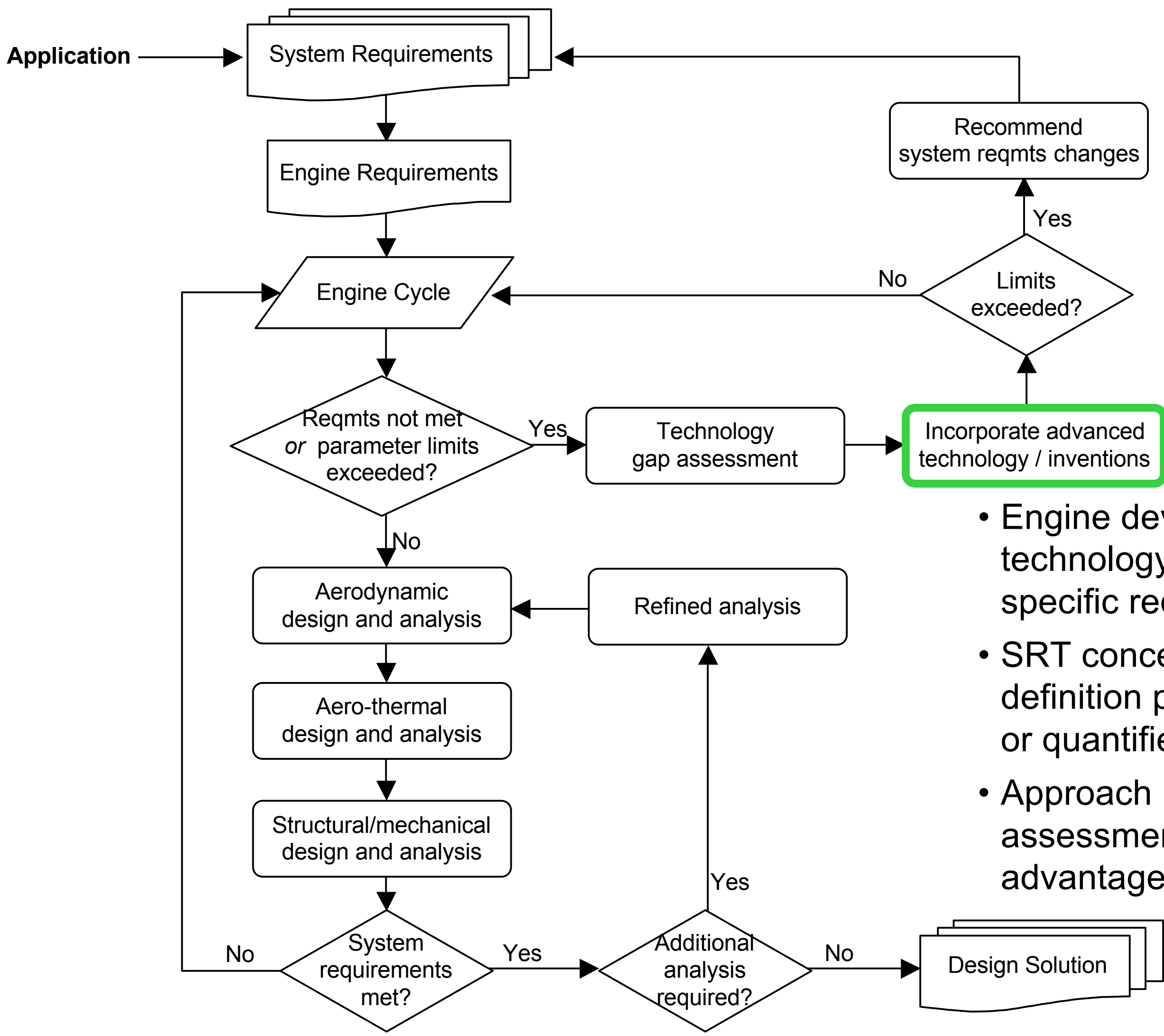
Agenda

- Objectives
- Approach
- Analytical Results
  - Thermal
  - Structural
  - Aerodynamic
  - Preliminary Cycle Definition
- Conclusions
- Phase 2 Recommendations
- Discussion

Objective

- Perform initial assessment and evaluation of the Single Rotor Turbine Engine Concept
- Phase I – Cycle Analysis and Design Feasibility evaluation
  - Perform initial analysis of the engine cycle and evaluate approaches to mechanical/structural design and resulting producibility techniques.
  - Identify advantages and/or limitations to the overall design, suggest relevant design enhancements and determine anticipated technology enabling issues to guide Phase 2
  - Work with LANL to identify potential commercial applications and perform initial analysis intended to determine optimum applications.

Engine Definition/Evolution Process



- Engine development process *pulls* technology and/or inventions to meet specific requirements for an application
- SRT concept is entering product definition process without a defined need or quantified advantage
- Approach must be modified to include assessment of SRT feasibility, limitations, advantages, and market positioning

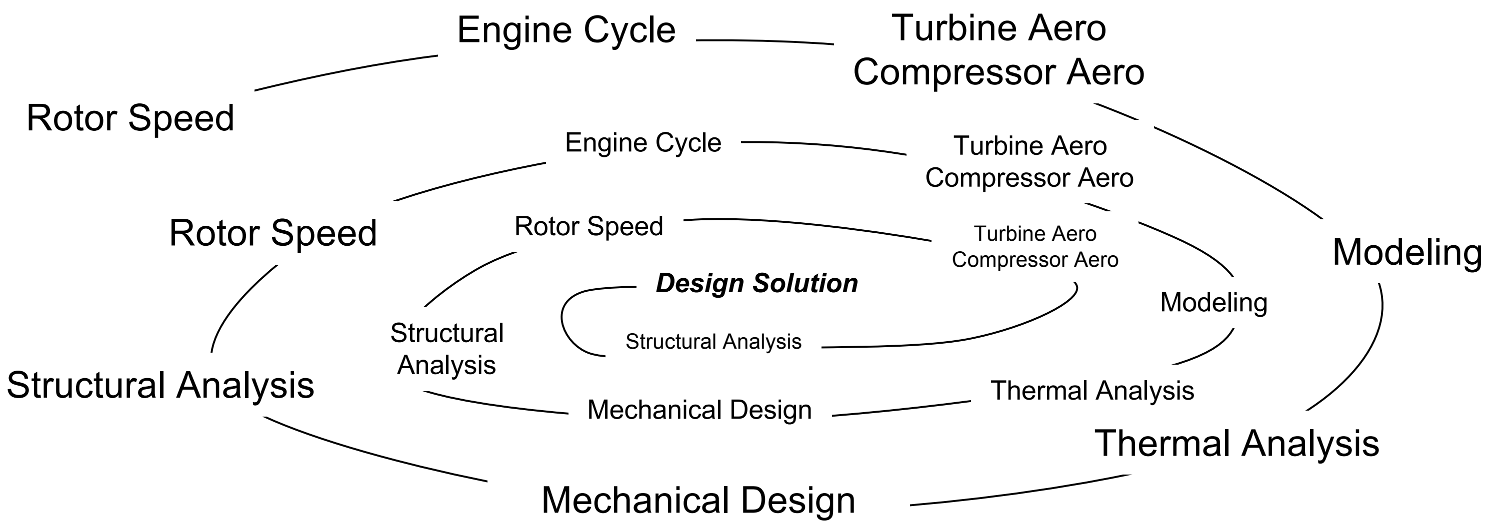
SRT Concept Evaluation Approach

Phase 1

- Identify candidate applications for single rotor turbine concept
- Compare cycle parameters to similarly sized gas turbines
- Assess comparative advantages and limitations and scalability of design
- Develop notional engine cycle to establish initial cycle parameters for concept evaluation and optimization
- Evaluate baseline SRT design (as provided by LANL) from aero-thermal and structural/mechanical perspective using initial cycle parameters
- Establish mechanical/structural limits (rotor speed, material thickness, producibility limitations). Develop geometric relationships to rotor speed for airfoil design and cycle iteration (initial design space)
- Refine engine cycle based on structural/mechanical limits
- Develop optimized airfoil geometry based upon design space
- Update model to reflect optimized airfoil geometry
- Iterate mechanical design, structural analysis, aerodynamic design, and engine cycle based on desired parameters
- Reassess inherent advantages and limitations of concept
- Identify technology gaps
- Narrow field of applications to focus development and evaluation activities
- Define engine system requirements and development approach

Phase 2

Design Iteration Process



- Use airfoil cross sectional area relationship to rotor speed (stress) to define turbine airfoil aerodynamic design
- Update engine cycle with resulting turbine characteristics
- Update 3D model geometry to include updated impeller and turbine airfoils
- Update mechanical design and structural analyses. Update rotor speed limit
- Iterate as required to obtain satisfactory cycle definition and design solution, permitting 3D analyses to commence

Single Rotor Turbine Attributes

Advantages

- Packaging advantages in turbofan applications
- Lower cost and weight than conventionally cooled designs through reduced part count
- Potential sealing improvements and clearance control
- Allows higher turbine inlet temperatures than un-cooled designs in small size engines* (< 1 lbm/s core flow)

Challenges

- Reduced wheel speed for given allowable stress levels
  - Necessitates increased stage count and/or loadings or lower cycle pressures
- Reduced Compressor Efficiency
- Producibility

* In small sizes, conventionally cooled designs are impractical or impossible

- Agilis electronic Pro/E model of LANL ASRT
- Parametric model developed to evaluate airfoil and rotor optimization

Potential Advantages

- Power density compared to uncooled gas turbines
  - Up to 40% increase in thrust or power due to increased rotor inlet temperature
- Cost
  - Reduced part count due to integrated rotors and elimination of seals
- Size and Weight
  - Reduced part count due to integrated rotors and elimination of seals
  - Length reduction due to optimized engine arrangement

Candidate Applications

Engine Type and Use	Size	Weight	Cost	Operating Cost	SFC	Durability
			Figures of Merit			
Power generation						
- APU	X	X	X	X		X
- Jet Fuel Starter	X	X	X			X
- GPU			X	X		X
- Microturbine			X	X	X	X
Propulsion						
- Turbojet	X	X	X	X	X	X
- Turbofan	X	X	X	X	X	X

Quantification of figures of merit with and without SRT for each application for existing products required to determine largest and most appropriate market application

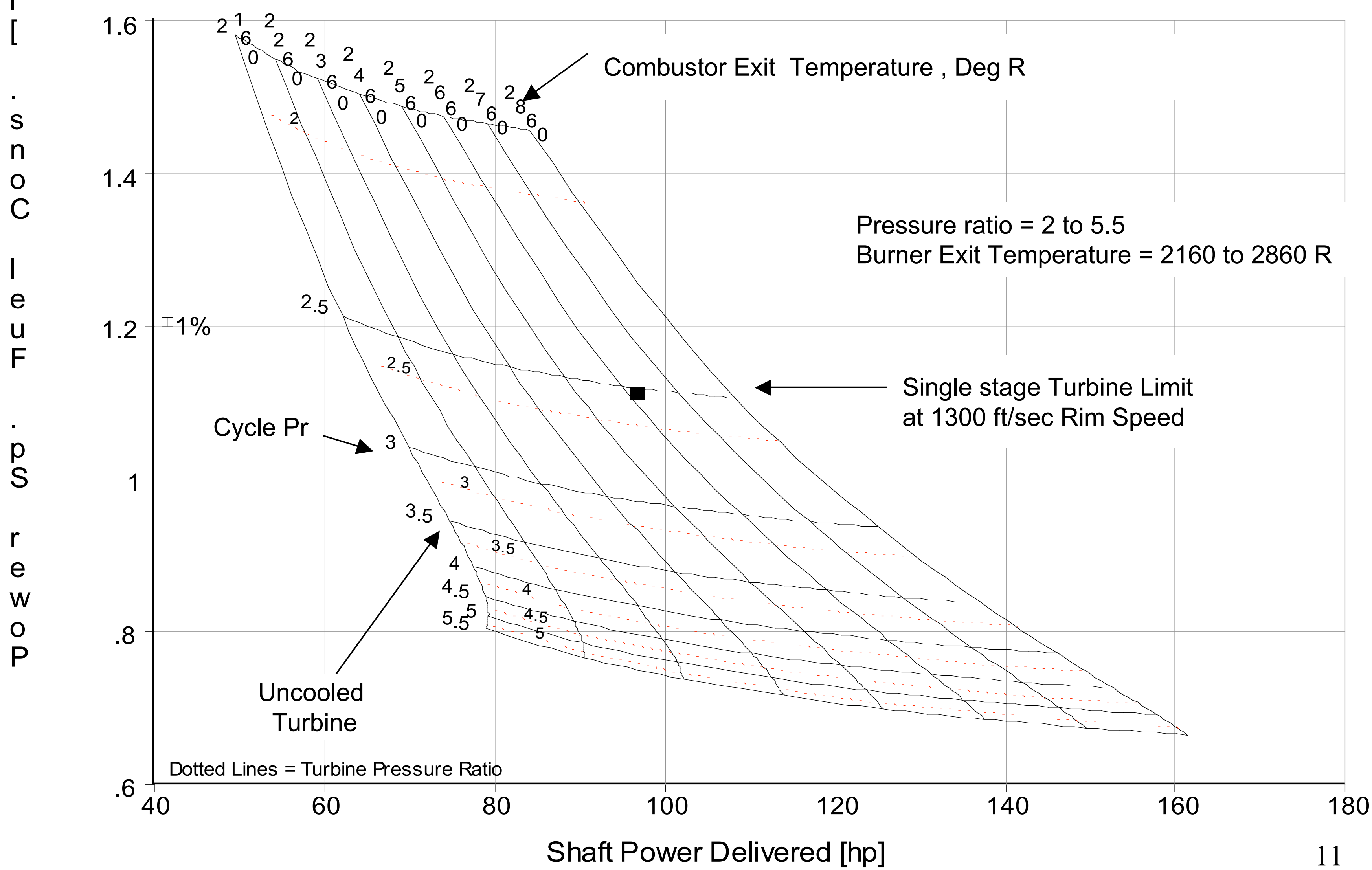
Cycle Comparison

Cycle Studies for a 1 lbm/sec Impeller Inlet Corr. Flow, Single Stage HPT*
(SLS, Std Day)

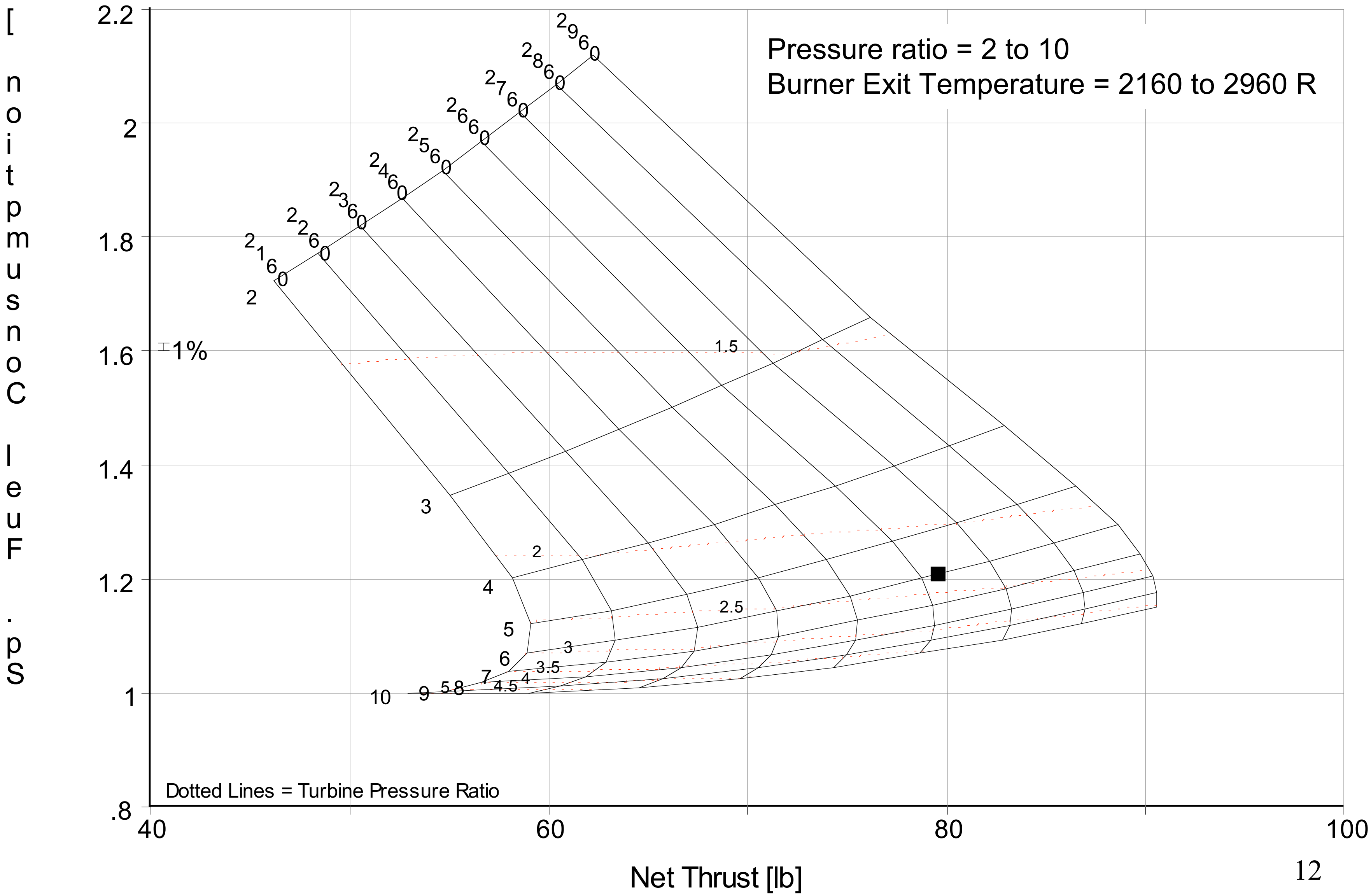
Configuration	OPR	Power	SFC	Advantages
Single Spool Turboshaft	2.5	97 HP	1.1	Cost, Length, Weight
Two Spool Turboshaft	6.0	145 HP	0.7	“
Single Spool Turbojet	6.0	70 lbf	1.2	“
Single Spool Turbofan	3.13	275 lbf	0.7	“
Two Spool Turbofan	8.0	380 lbf	0.42	“

* RPM= 85,000; T4= 2685 deg R; Eff Turb=82% (Adiabatic); Eff Comp=77% (Polytropic)

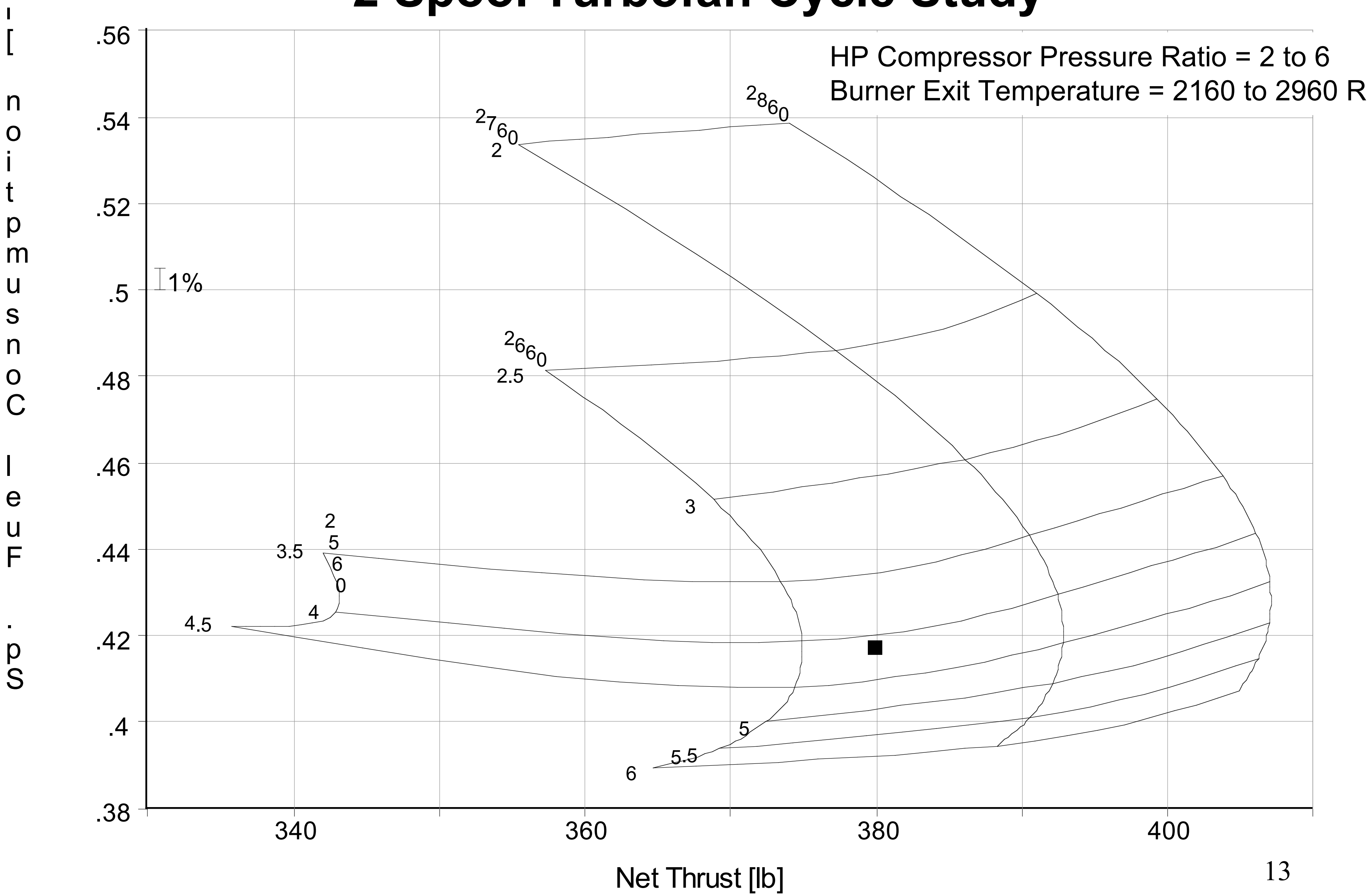
Turboshaft Engine Parametric Study



Turbojet Cycle Parametric Study



2 Spool Turbofan Cycle Study



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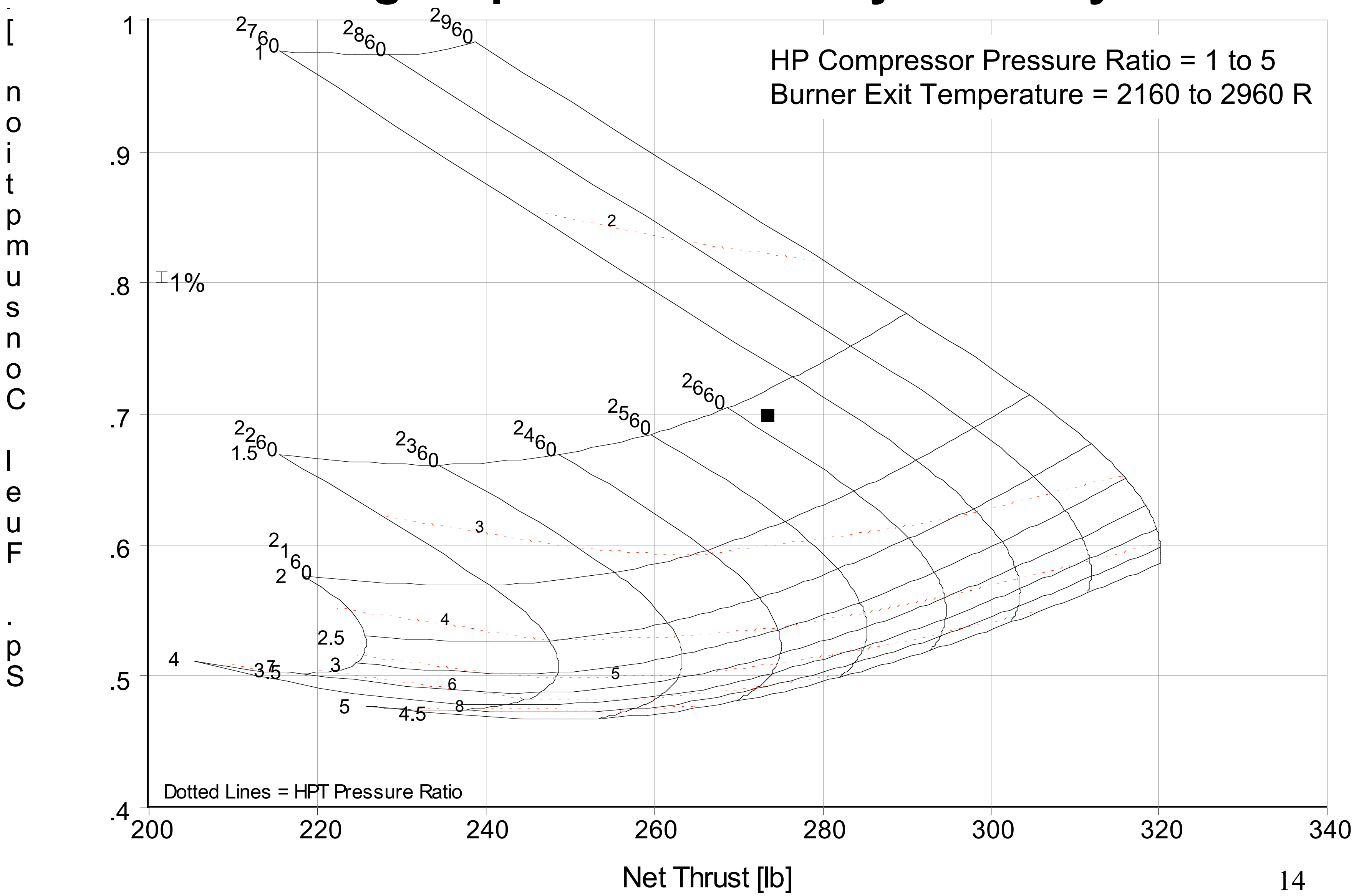
Single Spool Turbofan Cycle Study



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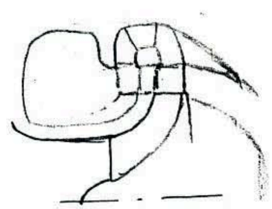
Baseline Study Engine Cycle

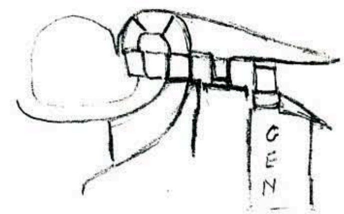
- Single Spool Turboshaft

Air Flow	1 lbm/sec
Fuel Flow	0.0299 lbm/sec
Power	97 HP
PSFC	1.1 lbm/hp/hr
Pr	2.517
Eff-Comp	0.74
Eff-Turb	0.82
Combustor Pressure Drop	3%
Fuel Heating value	18552.4 Btu/lbm (Jet Fuel)
RPM	85,000
Dimensions	6 in diam. 6 in length

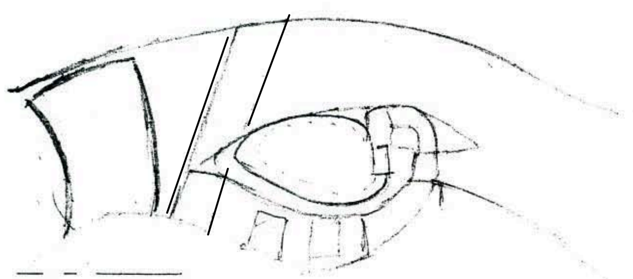
Potential Engine Configurations



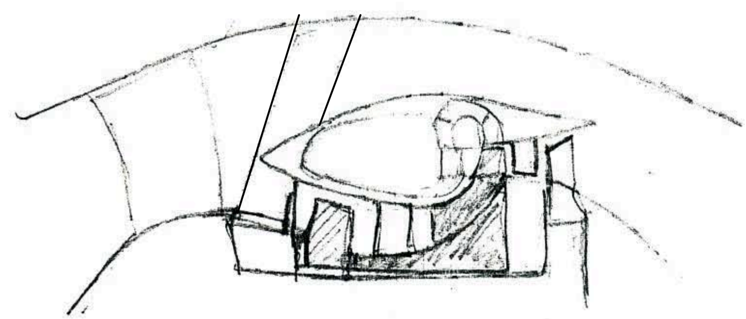
Turbojet



Turboshaft (+Power Turbine)



Single Spool Turbofan



2 Spool Turbofan

Analytical Results

2D Structural Analysis

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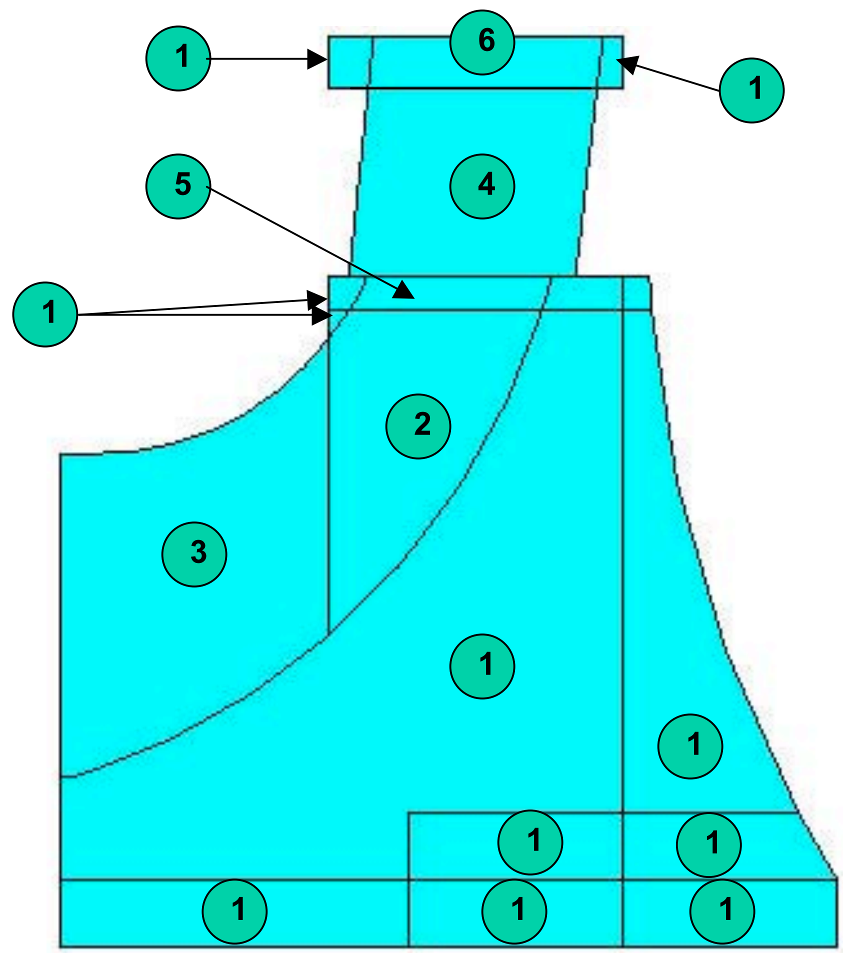
Analysis Study Assumptions/Criteria

Assumptions:

- Supplied CAD geometry used for analysis with modification
  - *Additional full hoop material added to aft portion of model for better stress distribution*
  - *Shaft insert holes filled to simulate integral shaft for stress reduction*
- Use 100,000 rpm rotation speed for the baseline study
- Part will be made from MAR-M-247
- 2D model is sufficient for initial evaluation of conceptual design

Baseline Design – Material Map; MAR-M-247

Mat ID	*Solidity*
1	1.000
2	0.438
3	0.349
4	0.373
5	0.8231
6	0.7608



Baseline Design – FEM Description/Structural Boundary Conditions

FEM Characteristics:

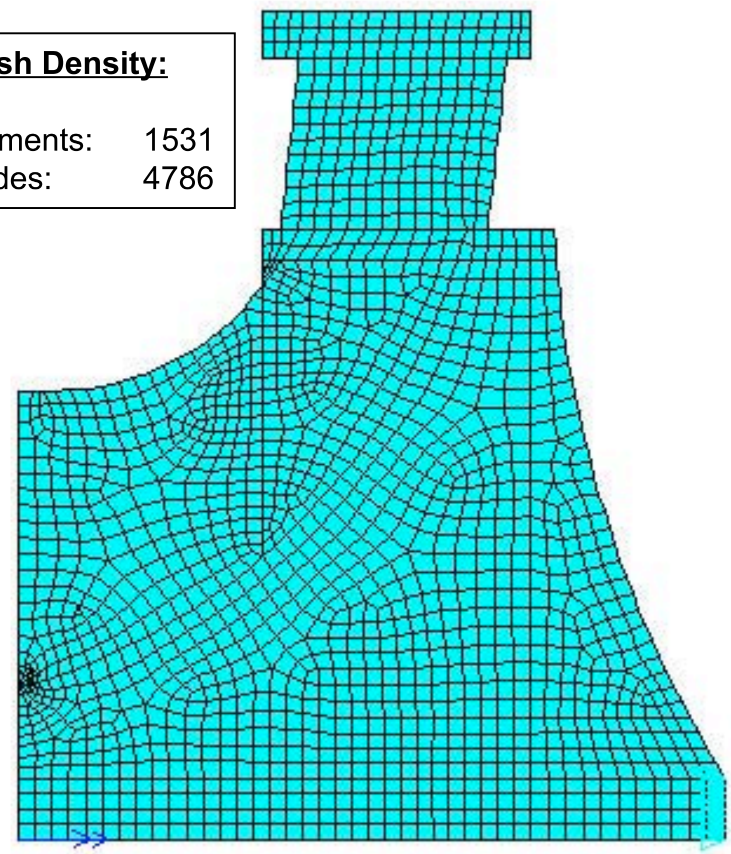
- 2D FEA of nominal geometry
- All regions modeled as “axi-symmetric”
- Material properties modified to simulate airfoils and holes (mass of ANSYS model = 1.066* mass of Agilis ProE model + mass of added portion)

Boundary Conditions:

- Aft of rotor held in axial direction
- Angular velocity of 100,000 rpm
- Thermals mapped as shown in thermal results section

Mesh Density:

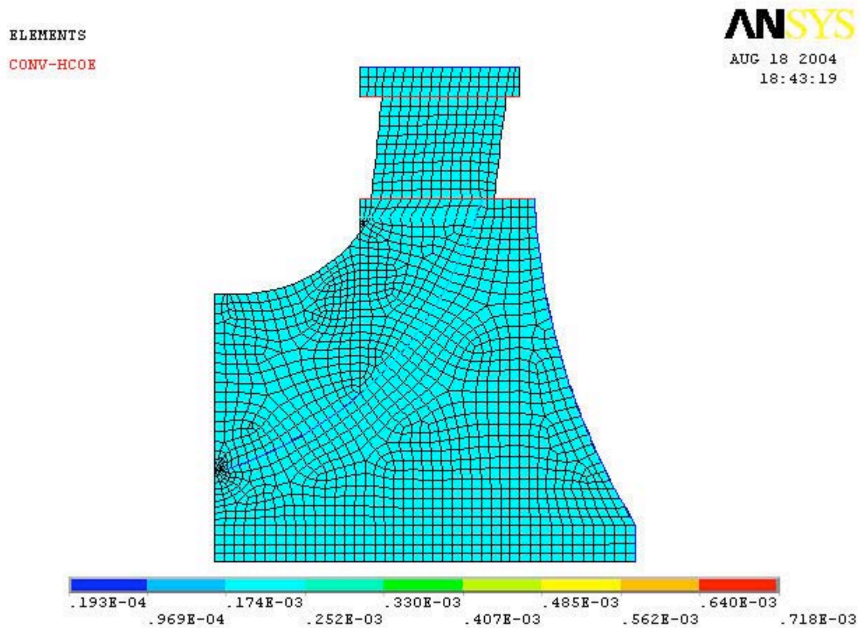
Elements:	1531
Nodes:	4786

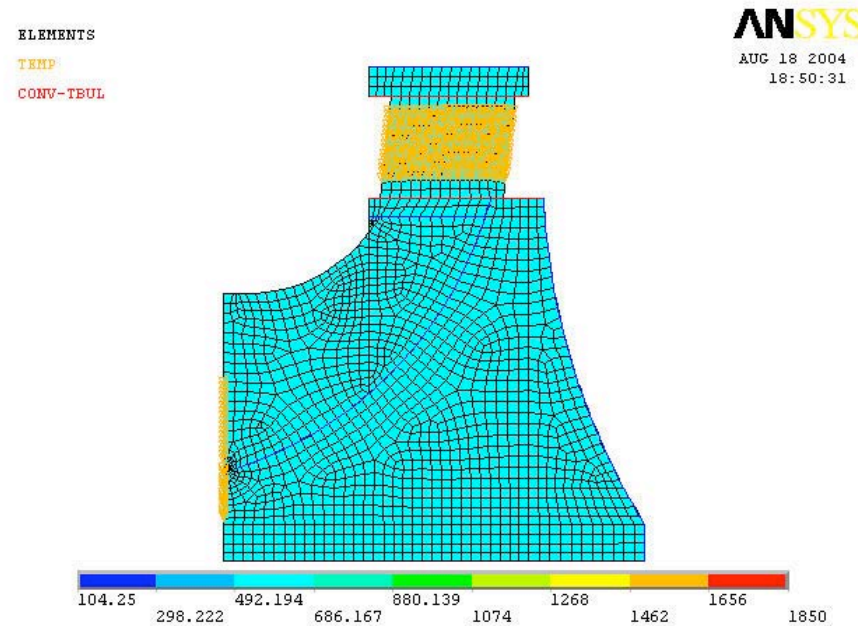


Baseline Design – Thermal Boundary Conditions

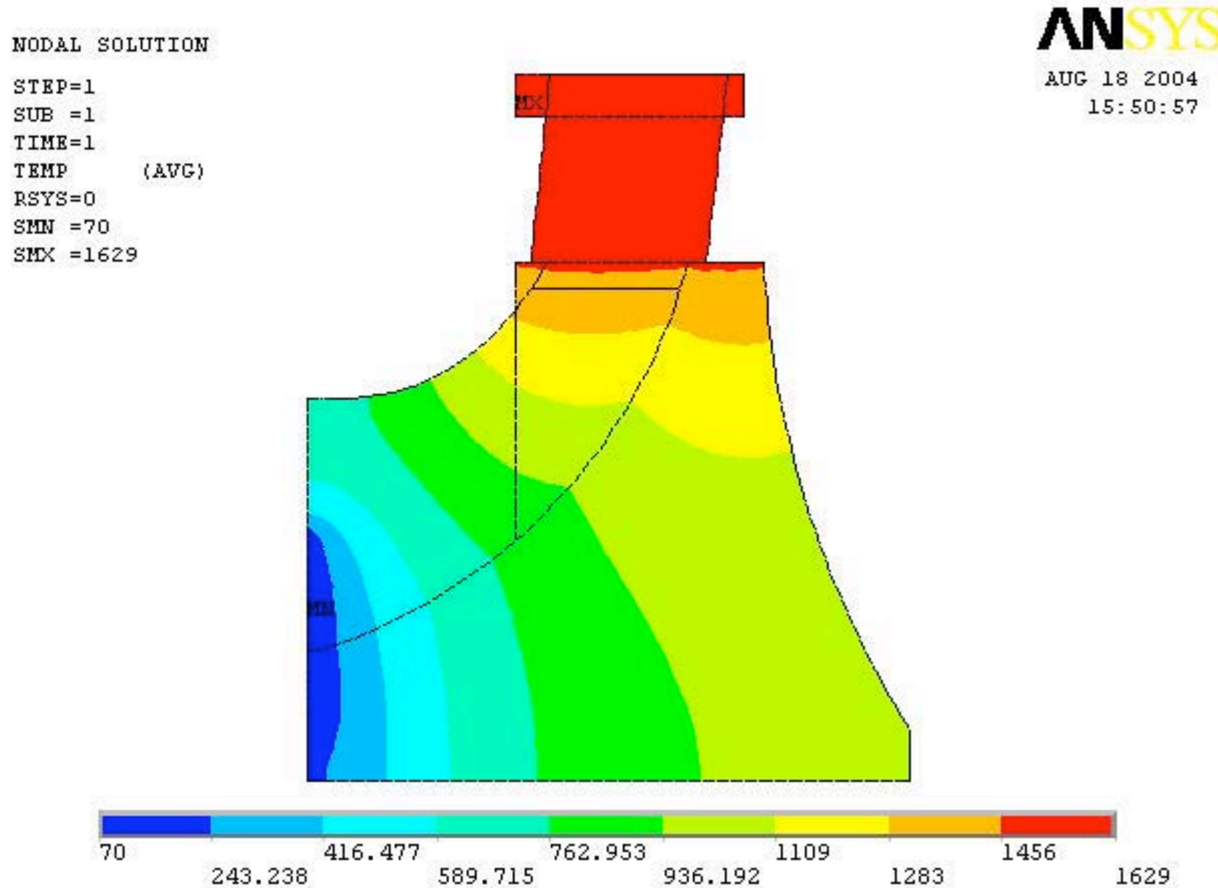
Boundary Conditions:

- Turbine airfoil held at 1540 F
- Compressor inlet held at 70 F
- Convection boundary conditions applied to turbine flow path surfaces and cooling side surfaces
- Convection boundary conditions applied as needed to determine a valid thermal profile (see below)





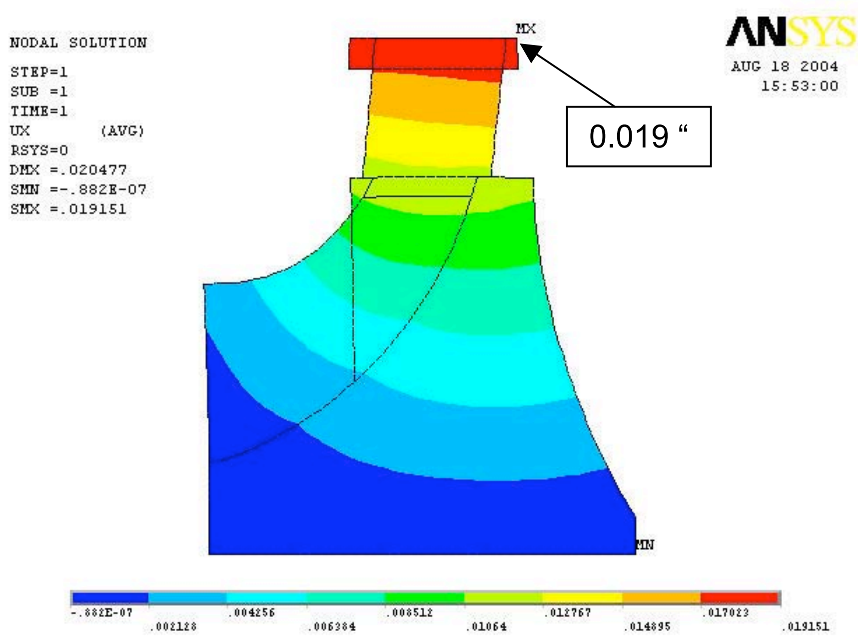
Baseline Design – Thermal Results



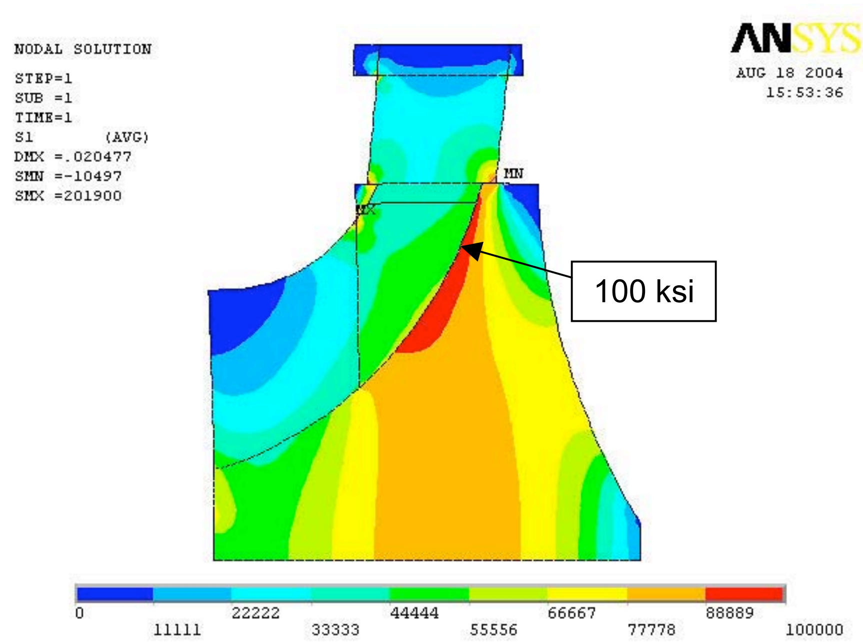
Baseline Design – Deflection/Stress Results

(100,000 rpm – Mechanical + Thermal Loading)

Radial Deflection



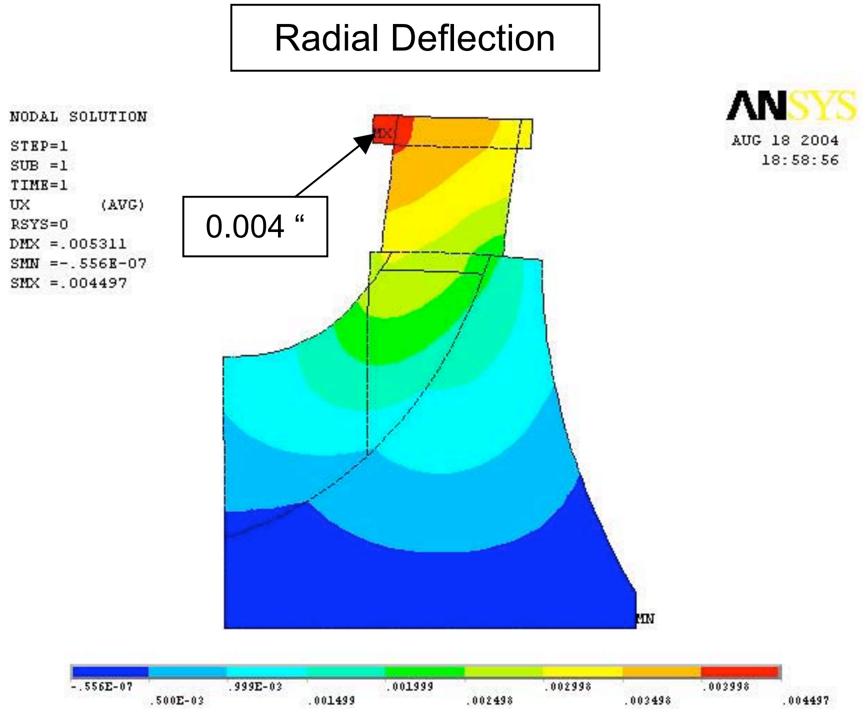
Tensile Stress

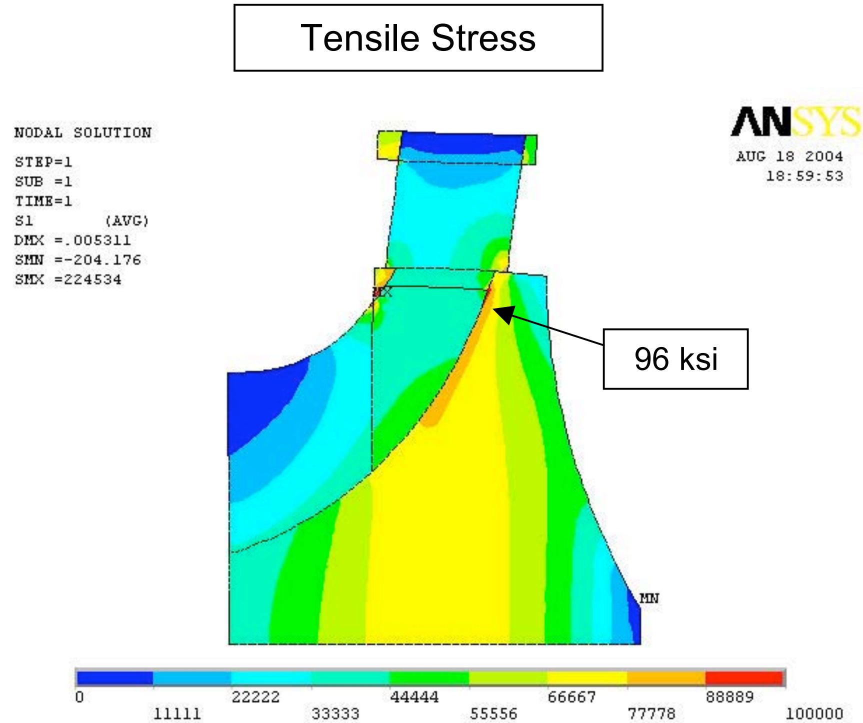


Radial force due to turbine airfoil and OD ring pull = 141,000 lbs

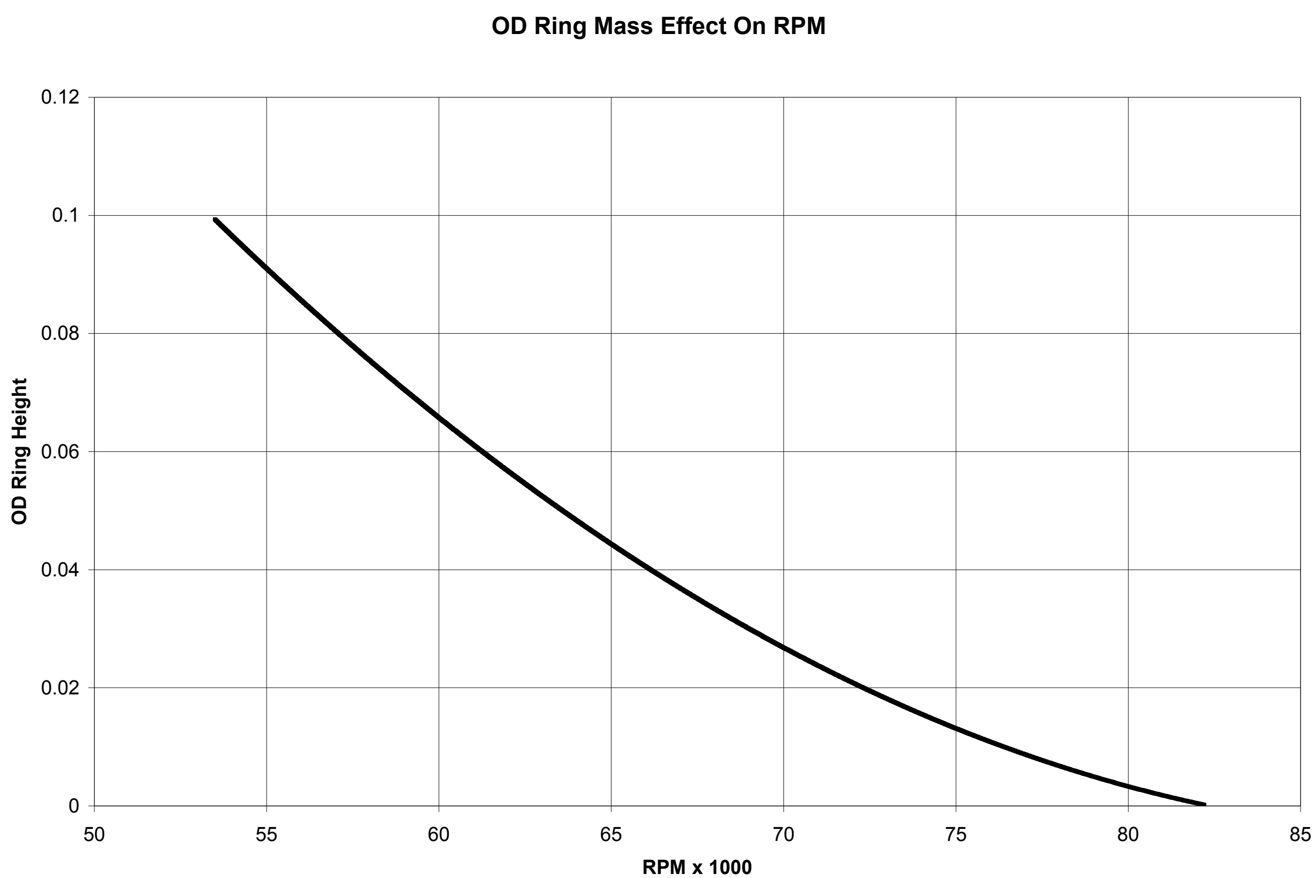
Baseline Design – Deflection/Stress Results

(100,000 rpm – Mechanical Load Only)



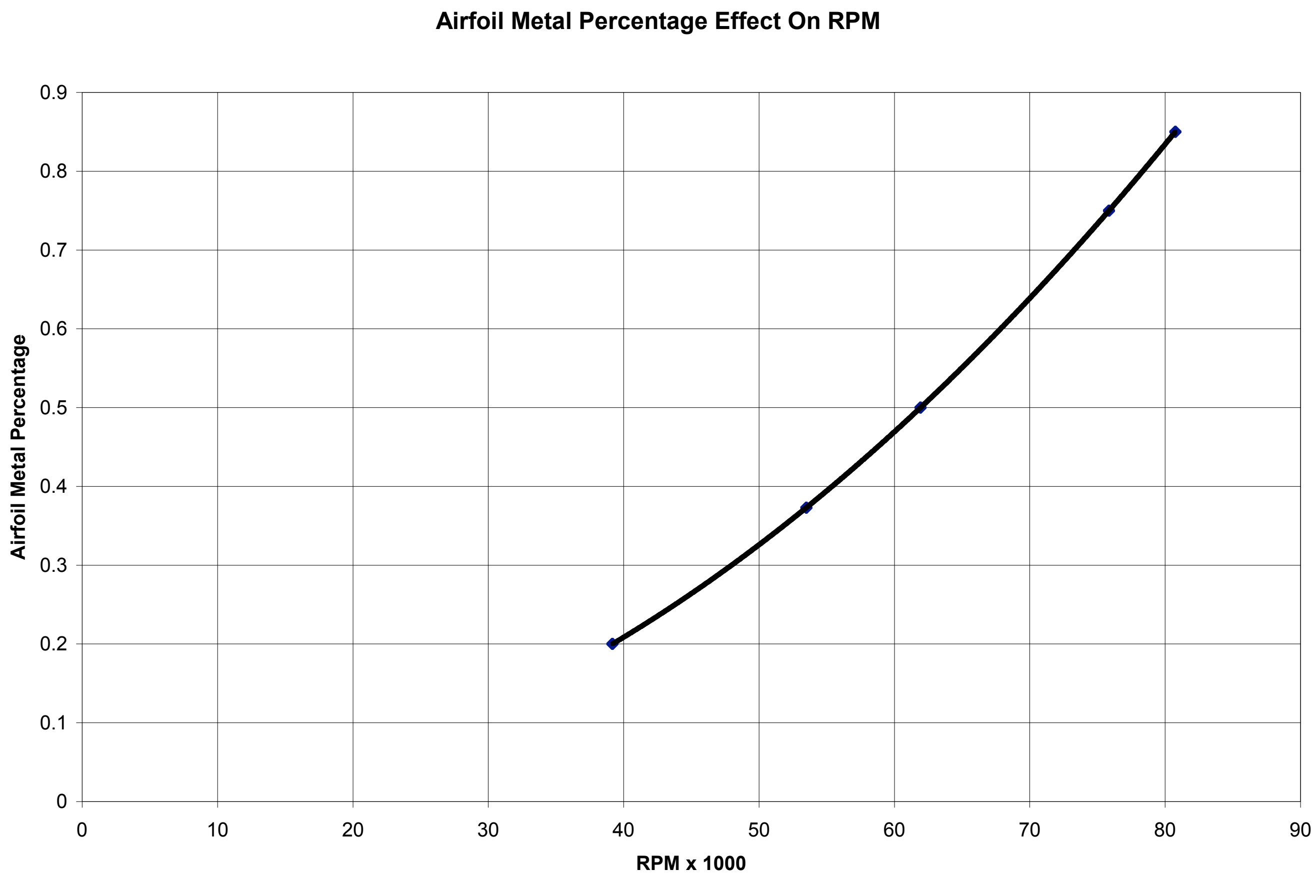


OD Ring Height Effect on Allowable RPM



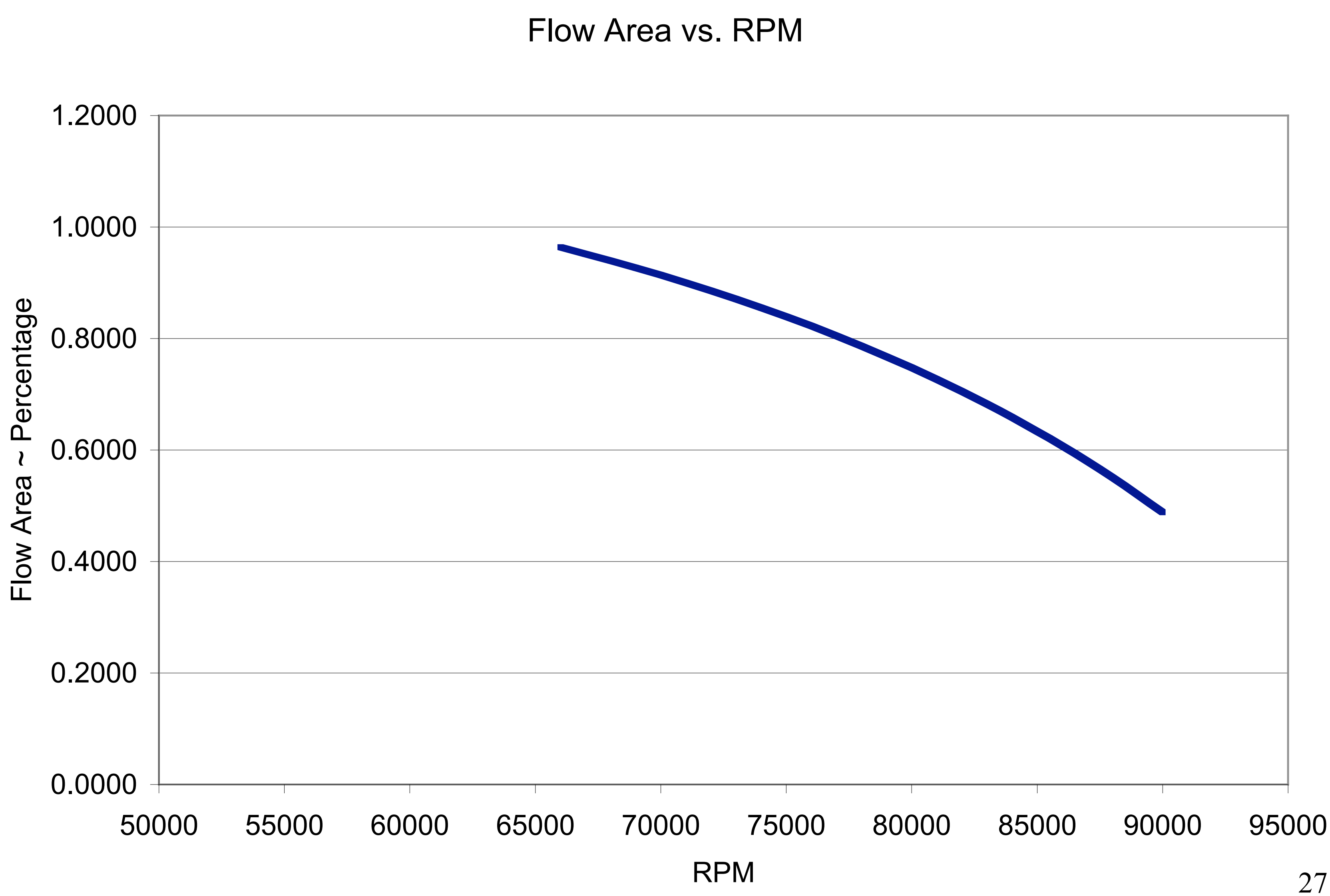
2D Analysis used to guide initial assumptions for next phase

Airfoil Cross Sectional Area Effect on Allowable RPM (Airfoil Mass Held Constant)



2D Analysis used to guide initial assumptions for next phase

Rotor Speed Relationship



2D Analysis Study Summary / Recommendations

Summary:

- The compressor rim stress is driven by rotational speed. This analysis does not capture circumferential thermal fights between the turbine airfoils and the rings.
- High stress region shown in the compressor does not have a k_t applied as would be necessary when dealing with an airfoil fillet. Detailed 3D analysis is necessary to characterize these stresses.
- The speed of the rotor is currently limited by the load capability of the turbine airfoils (σ =P/A calculation)
- Limiting RPM at 95,000 rpm requires turbine airfoil cross section = 3.2 in^2. Varying the OD ring thickness may offer improved rpm capability

Recommendations:

- Optimize OD ring or increase the cross sectional area of the turbine airfoils in order to reduce P/A stress in the turbine airfoils.
- Investigate use of thermal barrier coating (TBC) to reduce metal temperature which will increase overall strength capability of the part
- Perform further detailed design work with 3D geometry to allow assessment for the low cycle fatigue (LCF) life in addition to strength limits (design systems for the gas turbine industry require durability and fatigue assessments)

Phase 1 Conclusions

- Preliminary analysis indicates SRT concept is feasible and usable in numerous applications – No “show stoppers”
- SRT concept offers significant power density ratio improvement over conventional un-cooled gas turbines
- Part count reduction and associated weight and acquisition cost reductions are main attributes when compared to cooled gas turbine
- Performance benefits are limited by rotor speed
- Rotor speed is limited by turbine airfoil load capability
- Turbine airfoil geometry will determine cycle attributes

Phase 2 Recommendations

- Complete design iteration process of a baseline design to better quantify the comparative performance measures and limitations, and to guide application selection
- Evaluate ultra-small gas turbine to exploit inherent cooling advantages of the SRT concept
- Perform limited 3D structural and thermal analyses
- Determine desired figures of merit for target applications
- Quantify attributes of optimized configuration
- Select preferred application and associated engine concept
- Determine technology gaps and plan to resolve gaps
- Assess development risks
- Develop risk mitigation plan
- Develop engine demonstration plan
- Propose engine demonstration plan to funding agencies